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Definition of "banner clouds" based on time lapse movies

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Abstract. Banner clouds appear on the leeward side of a mountain and resemble a banner or a flag. This article provides a comprehensive definition of "banner clouds". It is based primarily on an extensive collection of time lapse movies, but previous attempts at an explanation of this phenomenon are also taken into account. The following ingredients are considered essential: the cloud must be attached to the mountain but not appear on the windward side; the cloud must originate from condensation of water vapour contained in the air (rather than consist of blowing snow); the cloud must be persistent; and the cloud must not be of convective nature. The definition is illustrated and discussed with the help of still images and time lapse movies taken at Mount Zugspitze in the Bavarian Alps.

1 Introduction

According to the Glossary of Meteorology (Glickman, 2000) a banner cloud is "a cloud plume often observed to extend downwind from isolated, sharp, often pyramid-shaped mountain peaks, even on otherwise cloud-free days." Well-known locations with frequent occurrences of banner clouds are the Matterhorn in the Swiss Alps or Mount Everest in the Himalayas.

Besides a number of drawings and photographs, there are very few measurements related to banner clouds documented in the scientific literature. We are aware of the work of Peppler (1927), who connected his observation of a single banner cloud event to upper air wind measurements and related the occurrence of the cloud to wind shear at the mountain top level. In 1947 Küttner (2000) measured temperature and humidity inside and outside a banner cloud at Mount Zugspitze (Bavaria, Germany) and found that the air inside the cloud can be 3–4 K warmer and 40–70% more humid than outside. Although this implies an extremely unstable stratification, the cloud top appeared fairly smooth and laminar. It was shown by Kuo (1963) and more recently by Benilov (2002) and Kirshbaum and Durran (2004) that, in an unstable environment, strong vertical shear may inhibit the onset of Rayleigh-Taylor instabilities. Thus the observed smooth cloud top could be the visual expression of a stabilizing effect of vertical wind shear.

Several qualitative arguments have been put forward in order to explain the origin of these clouds (e.g. Douglas, 1928; Küttner, 1949; Beer, 1974; Hindman and Wick, 1990). Probably the oldest dates back more than 100 years ago (Hann, 1896). Since then little progress has been made in explaining this phenomenon (see Houze, 1993). The only numerical modelling study to our knowledge was made by Geerts (1992b). Overall we think that there is surprisingly limited knowledge both observationally and theoretically about this phenomenon.

In December 2002 we installed an electronic camera close to the summit of Mount Zugspitze in the Bavarian Alps providing us with daily time lapse movies. These movies are used to identify banner cloud situations and to investigate their temporal and spatial evolution. Soon we realised that we had to develop a comprehensive definition of this phenomenon in order to draw the subtle line between (what we believe are) true banner clouds and other phenomena, which only resemble banner clouds. The wealth of information from the movies proved invaluable for this endeavour.

It is the main goal of the current article to present this definition (Sect. 4) and to illustrate and discuss its essential ingredients by selected stills and movies (Sect. 5). Before we do so, however, we briefly summarise various existing theories regarding the formation of banner clouds (Sect. 2). This is considered important because defining and understanding a phenomenon is like two sides of the same coin. The movies presented are an essen-

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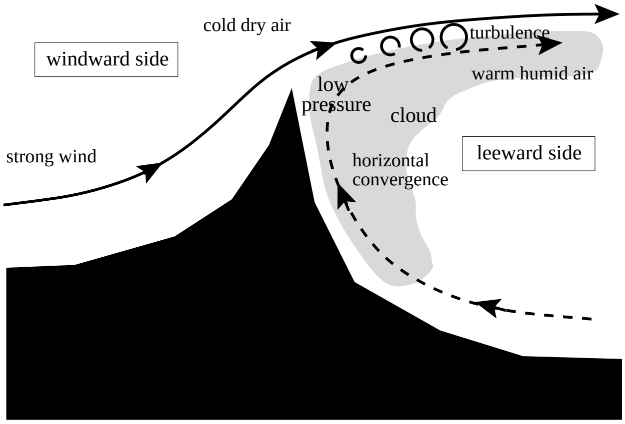

Fig. 1. Schematic showing the main features of a banner cloud in a vertical section.

tial part of this article. They are embedded in this pdf-document and can additionally be found in the supplemental material (http://www.atmos-chem-phys.net/7/2047/2007/acp-7-2047-2007-supplement.zip). Technical details how to view the movies are provided in Appendix A.

2 Existing theory

There are basically three distinct lines of argument to explain the formation of a banner cloud. According to them, saturation and condensation is due to

1. adiabatic cooling owing to pressure reduction along trajectories which originate on the windward side of the mountain, (Humphreys, 1920; Grant, 1944; Huschke, 1959; Beer, 1974),

2. mixing of cold air from the mountain boundary layer with warmer air from above (Humphreys, 1920),

3. adiabatic cooling in an updraft on the leeward side of the mountain (Hann, 1896; Douglas, 1928; Hindman and Wick, 1990; Geerts, 1992a,b; Glickman, 2000).

According to argument 1, the flow deformation and acceleration at the crest is associated with a pressure reduction and corresponding adiabatic cooling along quasi-horizontal trajectories within the oncoming flow. However, Geerts (1992a) pointed out that even for strong wind this temperature reduction is too small to explain the observed banner clouds. Moreover, our examples in Sect. 5 indicate that banner clouds can also be observed at moderate wind speeds.

The basic idea of argument 2 is that the cloud forms as mixing fog, i.e. through mixing of cold air from the boundary layer close to the mountain with warmer air from the overlying atmosphere. Geerts (1992a) pointed out that in most cases there is no reason for the air on the leeward side to be colder than the air in the oncoming air stream. But even so, assuming that there is a cold pool on the leeward side, mixing fog should form where the two air masses meet. In general this is along the separating boundary layer, which is attached to the ridge. Accordingly one expects the cloudy layer along this interface to be thinnest at the ridge, because this is the first point of contact between the two air masses. The cloud should grow in depth with increasing distance from the ridge corresponding to a growing mixing layer. In contrast, typical banner clouds are shaped the opposite way, i.e. they have maximum depth near their point of attachment and taper out away from the mountain. So the argument involving mixing does not appear very plausible, either.

The most accepted argument is 3, which evokes upwelling on the leeward side of the mountain as shown schematically in Fig. 1. Scorer (1972) identifies this as a special case of flow separation with the ridge as the point of separation. Assuming identical humidity distribution on both sides of the mountain, air parcels in the leeward updraft must originate at lower levels than air parcels which are lifted on the windward side (otherwise a cloud would occur on both sides of the mountain). The windward-leeward asymmetry of a banner cloud in this argument is primarily associated with a corresponding asymmetry of the flow field, with a larger upward displacement in the lee favoring leeside cloud formation.

Different arguments have been put forth to explain the primary cause of the upwelling in the lee of the mountain. The updraft can be considered as due to

A. the pressure minimum in the lee of the mountain top (Hann, 1896; Douglas, 1928; Banta, 1990; Hindman and Wick, 1990; Glickman, 2000)

B. confluence in vortices on the leeward side (Geerts, 1992a,b)

C. turbulent momentum transport between the air flowing over and around the mountain and the air on the leeward side of the mountain.

We think that all three arguments are viable and part of the whole picture. Note that all three arguments can be considered as “dynamical” requiring an environmental wind of decent strength. None of them invokes positive buoyancy to explain the updraft. This motivates us to exclude purely convective clouds from our definition (see Sect. 4).

Both A and C can be realised in purely two-dimensional flow across a horizontal ridge with slab-symmetric geometry. In this case the dashed streamline in Fig. 1 indicates the vortex with horizontal axis.

Argument B, by contrast, requires fully three-dimensional flow. Geerts (1992b) presented numerical simulations of moist air flowing over and around a peaked mountain. In a horizontal section through the mountain, the wake consists of two horizontal vortices with opposite sense of rotation. In fact, these two lee vortices are part of a single vortex tube

Fig. 2. Field of view of the camera with directions and the main landmarks.

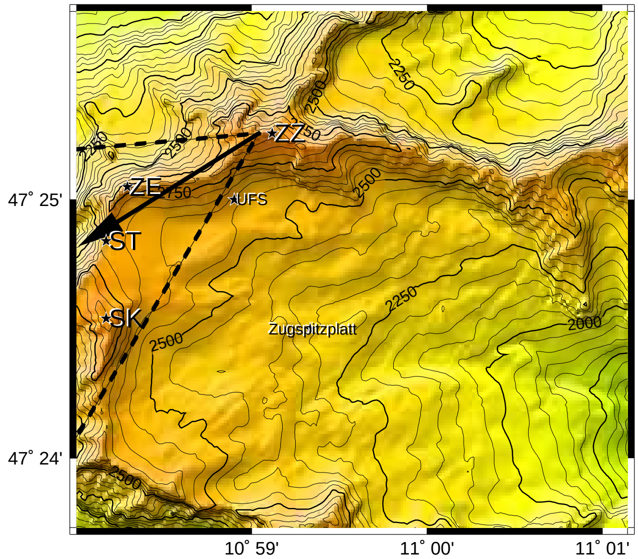

Fig. 3. Map of Mount Zugspitze with the main landmarks Zugspitze summit (ZZ), Zugspitzeck (ZE), Schneefernerscharte (ST), Schneefernerkopf (SK). The viewing direction of the camera is indicated by the solid black line and the 55° field of view by the dashed lines.

which is folded and skirts the ridges of the peaked mountain (rather than being straight, as above for the two-dimensional horizontal ridge). The confluence associated with this folded vortex tube is at least partly compensated by upwelling in the lee of the mountain. In a vertical section through the axis of symmetry this secondary circulation follows the dashed line in Fig. 1. Because argument B works for three-dimensional peaked obstacles only, Geerts (1992a) restricted his definition to peaked mountains.

The phenomenon of a pair of horizontal vortices in the lee of a three-dimensional mountain has previously been discussed in the meteorological literature. Often it is explained in terms of boundary layer separation at the lateral sides of the mountain. Alternatively, Smolarkiewicz and Rotunno (1989) have shown that for small Froude numbers ($0.1 < Fr < 0.5$) it may be due to a purely inviscid mechanism. Whether the dominant mechanism is viscous or inviscid is likely to depend on the specific orography as well as on the meteorological conditions, and a firm assessment requires numerical modeling, which is beyond the scope of this paper. On the other hand, in the case of quasi two-dimensional mountain ridges (such as the ridge at Mount Zugspitze) we believe that the phenomenon is best described in terms of boundary layer separation, and the underlying mechanism must be essentially viscous.

As far as we know argument C has never been discussed so far in the context of banner clouds. At the ridge of the mountain there is strong shear separating the oncoming air (solid streamline in Fig. 1) from the leeward air (dashed streamline). Kelvin-Helmholtz instability may lead to fast growth of small disturbances (symbolised by the circular symbols in the figure). This results in turbulent transport of momentum across the shear layer accelerating the leeward air close to the top of the cloud (along the dashed streamline in Fig. 1).

3 Orography at Mount Zugspitze

Mount Zugspitze (2962 m above sea level) is the westernmost and highest peak of a larger mountain range, with most of the other summits reaching around 2800 m. To the west and north the mountain peaks are lower at around 2200 m.

Close to the Zugspitze summit there is a weather station of the German Weather Service (DWD), providing, amongst others, regular visual weather and cloud observations. Our electronic camera has been installed at the western side of the weather station looking towards the southwest along the western ridge (see Figs. 2 and 3). This ridge runs for about 500 m to the southwest descending from 2960 m to 2800 m, then turning westward and continuing for 500 m at roughly constant altitude (2800 m) to the Zugspitzeck (ZE in Fig. 3). From here the ridge continues for about 2 km to the south with the Schneefernerkopf at 2874 m (SK in Fig. 3) being the highest peak and the Schneefernerscharte at 2700 m (ST in Fig. 3) being the deepest gap. East of the Zugspitze summit the ridge forks into two. One extends in the NE-direction. The other one runs in ESE-direction for about 2 km, slightly descending to 2700 m, from where it continues further east.

The area enclosed by these ridges is called “Zugspitzplatt”, a rough terrain mainly covered by ice, snow, boulders, and gravel. The Zugspitzplatt slopes in southeasterly direction from about 2600 m at the foot of the ridges to about 1700 m at the eastern boundary of Fig. 3, where it drops 300 m down to a narrow valley running eastward. In contrast to this rather gentle slope to the southeast, the north and west sides of the mountain are dominated by very steep rocks dropping from around 2800 m down to 1700 m, from where forested slopes reach down to the valley floor at around 1000 m.

Depending on wind direction and other meteorological conditions, banner clouds can form at all ridges described above. Here, we focus on the ridge running westward from the Zugspitze summit to Zugspitzeck. It is well captured by the field of view of the camera (Fig. 2). Also, it was this very ridge on which Küttner (2000) made his measurements more than 50 years ago.

Images are stored every 5 s during the day and are automatically concatenated every night to produce a movie. At the standard rate of 25 frames per second, this corresponds to a 125-times-fold time lapse movie. The movies are visually inspected for banner cloud episodes, and appropriate sequences are cut out.

Banner clouds at Mount Zugspitze occur throughout the year. We observed approximately 20 to 30 events per year for the period 2002 to 2006, with a single event lasting up to several hours. The true number of banner clouds should be higher, because our observations are restricted to daytime and there is no reason to believe that banner clouds do not occur during the night. There is a preference for occurence during the summer months, but this, too, should be interpreted with care for the same reason as above.

The slowest windspeed observed during a banner cloud event is about 2 m/s. The horizontal extent of the banner clouds is highly variable, ranging from several decameters to several hundred meters. It is difficult for us to quantify their vertical extent, since no camera was positioned below the cloud. It appears that the vertical and horizontal extent of the cloud are correlated to some degree.

Banner clouds are often associated with post frontal weather situations. Nearby radio soundings show mostly stable stratification around and below the level of Zugspitze summit during most of the observed banner cloud episodes (see also Sect. 5). An investigation of lifting condensation levels showed that it is in general not possible to derive a lower boundary of the cloud. Condensation can occur at many levels below the mountain summit, provided that the air is lifted sufficiently. Thus the cloud thickness seems to be connected to the vertical extent of the leeward updraft, which in turn should depend on the wind speed at mountain summit and the static stability in the lee. It can be summarized that the specific shape and size of the observed banner clouds is highly variable and strongly depends on the meteorological situation. We believe that important determinants are the moisture profile, the static stability and the wind speed around the ridge.

4 Definition of "banner clouds"

Based on the scrutiny of numerous time lapse movies, and with previous theoretical considerations in the back of our minds, we arrive at the following three criteria as defining essentials of a banner cloud.

I. A banner cloud is a cloud which occurs exclusively on the leeward side of a mountain. It is located in a fixed relation with respect to orography and touches the ground at least at the top of the ridge or peak. If there is some other cloud on the windward side, the banner cloud must not be connected to that cloud.

II. A banner cloud must not consist of snow crystals blown off the snow covered mountain. Rather, it consists of condensate which originates from water vapour contained in the air.

III. A banner cloud is persistent, i.e. it lives significantly longer than the time it takes for an air parcel to travel the horizontal extent of the cloud.

Criterion I contains the usual ingredients as given, e.g., in the Glossary of Meteorology (Glickman, 2000). The close connection of the cloud with orography implies that the cloud is pretty much fixed in space despite the wind, which can be rather strong. The constraint to appear on the leeward side only distinguishes the banner cloud from a cap cloud, which forms on both sides of a mountain due to the lifting and adiabatic cooling of the air flowing over the mountain. Banners of blowing snow are often observed in winter or at sufficiently high mountains. Since these banners are not the direct result of thermodynamical processes involving phase transitions, they are not considered as clouds and, therefore, excluded by criterion II. Criterion III excludes short-lived episodes of fractus clouds which happen to come close to the ridge. The cloud must be quasi-stationary with the air flowing through the cloud.

In most cases the above three criteria are sufficient to unambiguously define a banner cloud. Occasionally, however, there may be ordinary convective clouds in the lee of the mountain or the ridge which superficially resemble a banner cloud. We propose to exclude clouds arising from positive buoyancy, leading us to an additional fourth criterion:

IV. A banner cloud is not convective in character, i.e. the upwelling causing the cloud is not primarily due to positive buoyancy. Rather, the upwelling on the leeward side is associated with the flow over and around the mountain.

This last criterion is the most contentious one. In fact, it turns out that there is a continuous transition between convective clouds and (what we consider as) banner clouds. The issue will be further discussed in the following section. The criterion also excludes purely thermal wind systems like slope

Fig. 4. Still image of movie `m04.mpg` from 27 August 2005 19:07–20:20, an example for a typical banner cloud. Wind blowing from the north i.e. from right to left. Wind speed at Zugspitze summit is 3.8 m/s at 10°. The radio sounding of Munich from 28 August 2005 00:00 UTC shows a Brunt-Väisälä frequency of 0.0096 s^{-1}. For the movie see supplemental material: http://www.atmos-chem-phys.net/7/2047/2007/acp-7-2047-2007-supplement.zip and Appendix A.

Fig. 5. Example of a cap cloud at mount Zugspitze from 6 July 2003 07:26. Wind blowing from the west i.e. from right to left. Wind speed at Zugspitze summit is 7.4 m/s at 280°. The radio sounding of Munich from 6 July 2003 00:00 UTC shows a Brunt-Väisälä frequency of 0.011 s^{-1}.

winds and valley winds (Whiteman, 2000) as primary cause for banner clouds, although it does not exclude the possibility that such thermal wind systems contribute to or modify their formation and maintenance.

5 Examples

We now present selected movie sequences in order to illustrate and discuss various aspects of our definition. Figures 4 through 10 show still images taken from these movies. In the caption below every still image there appears the name of the appropriate movie in the supplementary file http://www.atmos-chem-phys.net/7/2047/2007/acp-7-2047-2007-supplement.zip. To view these movies refer to Appendix A. Inside the movie the actual time (Central European Time = local average solar time +12 min) is shown in the top right corner. This time and the frame number are used to refer to specific events within the sequences. The captions include information about wind speed and direction measured at the weather station right on the Zugspitze summit. Additionally the Brunt-Väisälä frequency N is given, which was determined from an appropriate nearby radio sounding: either from Innsbruck located 35 km to the south-east, or from Munich/Oberschleissheim located 80 km to the north-east, depending on which was available, which was closer in time, and which better represented the meteorological situation shown in the movie. The Brunt-Väisälä frequency $N=\sqrt{g\theta^{-1}d\theta/dz}$ was calculated from finite differences between 700 hPa and 750 hPa.

5.1 A typical banner cloud

Figure 4 shows a typical banner cloud at Mount Zugspitze. The movie sequence starts at 19:07 with only some scattered fractus clouds visible in the background at Schneefernerkopf. Condensation starts at the ridge leading to Zugspitzeck, with a clear indication of the updraft along the ridge. By 19:38 (frame 375 of the movie) a cloud has developed. It continues to exist for 30 min until 20:11 (frame 814), when it starts to dissolve. Obviously, the cloud is attached to the ridge; it touches the ground not only along the ridge but even further down the Zugspitzplatt (criterion I). There are no clouds on the windward side of the ridge. Pieces of clouds which temporarily obscure the view originate from the ridge just in front. The opaqueness of the cloud suggests that it consists of water droplets. Moreover, there is hardly any snow on the mountain which could be blown off by the wind. Thus, we believe that criterion II is satisfied. The cloud remains visible for more than 30 min, while the time a cloudy air parcel takes to travel from the ridge to the outer edge of the camera's viewing angle is about 2 min. Thus the cloud can obviously be considered as persistent (criterion III). The cloud does not show any indication of a convective nature (criterion IV) and the updraft appears to be clearly associated with the wind crossing the ridge.

5.2 A cap cloud

Figure 5 (without a movie) shows an example for a cap cloud to illustrate the difference to a banner cloud. The cloud covers both the windward and leeward side of the ridge. Its top surface follows the curvature of the streamlines crossing the

Fig. 6. Still image of movie `m06.mpg` from 29 March 2003 09:46–10:19, an ambigous case. Wind blowing from the north i.e. from right to left. Wind speed at Zugspitze summit is around 1.5 m/s at 340°. The radio sounding of Innsbruck from 29 March 2003 03:00 UTC shows a Brunt-Väisälä frequency of 0.0095 s^{-1}. For the movie see supplemental material: http://www.atmos-chem-phys.net/7/2047/2007/acp-7-2047-2007-supplement.zip and Appendix A.

Fig. 7. Still image of movie `m07.mpg` from 5 August 2005 8:34–9:14, an example for a banner cloud transforming into a convective cloud. Wind blowing from the north i.e. from right to left. Wind speed at Zugspitze summit is 3.2 m/s at 10°. The radio sounding of Innsbruck from 5 August 2005 03:00 UTC shows a Brunt-Väisälä frequency of 0.0041 s^{-1}. For the movie see supplemental material: http://www.atmos-chem-phys.net/7/2047/2007/acp-7-2047-2007-supplement.zip and Appendix A.

ridge and is accordingly convex. Additionally its top appears much smoother than the banner clouds presented here indicating stable stratification.

5.3 An ambiguous case

Fig. 6 shows an ambiguous example. Based on the movie it is hard to conclude whether we are dealing with a banner cloud or not. Although the wind speed is very low (about 2 m/s), the initial development resembles that of a banner cloud: fog forms on the Zugspitzplatt and is drawn towards the ridge (9:46, frame 0 to 9:56, frame 110) where it is caught and turned over in the lee vortex. But then condensation starts on the windward side, too, and a lifting cloud forms covering the whole ridge. One may argue that the cloud formation on the windward side is not connected to the cloud on the leeward side and that the cloudy air from the windward side simply obscures the view onto the banner cloud. In this sense criterion I is satisfied and the cloud could be classified as a banner cloud. But apparently there is no spatial separation between the two clouds. The cloudy air from the windward side does not simply obscure the view, it merges with the banner cloud. The cloud as a whole does not resemble a banner cloud any more. Nevertheless we can not rule out that parts of this cloud still form due to upward motion in the lee.

5.4 Transition from a banner cloud to a convective cumulus cloud

The example from Fig. 7 shows the transformation of a dynamically driven banner cloud into a cumulus cloud which is triggered by orography. The movie starts with a cap cloud visible on both sides above the ridge. It originates from the lifting of air when crossing the ridge. Obviously, this cloud is not a banner cloud (violation of criterion I). It completely disappears by 08:45 (frame 132). Earlier (at around 08:37, frame 58) a banner cloud develops at the ridge below the cap cloud. Although it does not reach the thickness of the banner cloud from the previous example, it remains visible in the field of view for 37 min. At an early stage it appears to be dynamically driven by the wind blowing across the ridge. Towards the end of the sequence the cloud moves with the wind to the left and is not attached to the ridge anymore (violation of criterion I). It further develops stronger vertical movements indicating a transition to more convective behavior, which is a violation of criterion IV. Consider also the atmosphere above the mountains in the background, indicating the tendency for convective instability and cumulus growth during the sequence. The radio soundings of Innsbruck and Munich for the previous night show a strong inversion around 650 hPa, corresponding to an altitude of almost 800 m above the Zugspitze summit. Below this inversion convective clouds were free to develop, as can be seen in the background of the movie.

Fig. 8. Still image of movie `m08.mpg` from 6 October 2005 14:07–16:22, a case with different condensation levels. Wind blowing from the south i.e. from left to right. Wind speed at Zugspitze summit is 8.0 m/s at 150°. The radio sounding of Innsbruck from 7 October 2005 03:00 UTC shows a Brunt-Väisälä frequency of 0.0144 s^{-1}. For the movie see supplemental material: http://www.atmos-chem-phys.net/7/2047/2007/acp-7-2047-2007-supplement.zip and Appendix A.

Fig. 9. Still image of movie `m09.mpg` from 9 September 2005 17:01–18:07, an example for convective clouds transforming into a banner cloud. Wind blowing from the south east i.e. from left to right. Wind speed at Zugspitze summit is 5.0 m/s at 140°. The radio sounding of Munich from 9 September 2003 12:00 UTC shows a Brunt-Väisälä frequency of 0.0057 s^{-1}. For the movie see supplemental material: http://www.atmos-chem-phys.net/7/2047/2007/acp-7-2047-2007-supplement.zip and Appendix A.

5.5 Different condensation levels

In the example presented in Fig. 8 different condensation levels are apparent indicating different mechanisms for cloud formation. The movie sequence starts at 14:07, showing a cloud attached to the mountain on the north side of the ridge. It has been in existence (except for short periods) for several hours. Obviously, at this stage the cloud satisfies all criteria for a banner cloud: it is attached on the leeward side to the ridge (criterion I), it is opaque and, thus, likely to consist of water droplets (criterion II), it is persistent (criterion III), and its appearance does not indicate any convective character (criterion IV).

What makes this example so interesting are the cumulus clouds, which can be seen in addition to the banner cloud. Their condensation level is clearly at higher altitude than the condensation level of the banner cloud. There are two possible reasons. First, the air masses on the windward and leeward side could have different temperature, water content and stratification. Since the cloud lives for several hours, there would have to be a strong source of water vapor on the leeward side which continuously replaces the loss of vapour through the air flowing over the mountain. A second, more likely explanation is that the base of the banner cloud indicates the lifting condensation level (LCL see e.g. Banta, 1990, p. 231), while the base of the cumulus clouds indicates the cumulus condensation level (CCL).

The definition of the LCL assumes forced lifting and excludes mixing of the air parcel with the surrounding air. Condensation occurs at the level where the lifted parcel saturates. Since a banner cloud is due to dynamically forced lifting, its base is expected to be at the LCL. In contrast, the definition of the CCL makes two different assumptions. First, the air must be heated until it becomes positively buoyant. Second, the convective processes owing to the heating lead to a well mixed layer before the onset of any cloud. This implies a homogeneous water vapour mixing ratio in the layer below the cloud. Since in general the water vapour mixing ratio decreases with altitude, the assumed mixing reduces the vapour mixing ratio in the lower part of the mixed layer. Both the heating and the mixing lead to higher values for the CCL compared to the LCL. Using radio soundings we performed on that special day close to Zugspitze we found that the LCL was at 2500 m a.s.l., while the CCL was significantly higher.

After around 15:00 (frame 615) the movie shows the development of more convective clouds behind Schneefernerscharte and Schneefernerkopf. The condensation level of these clouds is still around 2700 m ASL and, thus, lower than the base of the cumulus clouds. After around 15:20 (frame 849) these clouds join with the higher lying cumulus clouds, while the banner cloud in the foreground continues to be dynamically driven. The development of the clouds behind Schneefernerscharte and Schneefernerkopf seems to be triggered by the insolation on the western slopes of Schneefernerkopf. Insolation heats the boundary layer, leading to updrafts which are strong enough to form convective clouds. Later in the evening (not shown in the movie) these convective clouds disappear, but the banner cloud in the foreground remains, demonstrating again its different origin.

Fig. 10. Still image of movie `m10.mpg` from 7 January 2005 15:50–16:11, an example for snow blown off the mountain. Wind blowing from the north i.e. from right to left. Wind speed at Zugspitze summit is 9.0 m/s at 350°. The radio sounding of Munich from 7 January 2005 12:00 UTC shows a Brunt-Väisälä frequency of $0.0122\,\mathrm{s}^{-1}$. For the movie see supplemental material: http://www.atmos-chem-phys.net/7/2047/2007/acp-7-2047-2007-supplement.zip and Appendix A.

5.6 Transition from a convective cumulus cloud to a banner cloud

Another interesting example is given in Fig. 9. It shows the transition from a buoyancy driven cumulus cloud to a dynamically driven banner cloud. The sequence starts with a convective cloud on the west side of the mountain at Schneefernerscharte. Some fast growing convective clouds are visible in the valley to the west. While these clouds vanish at around 17:40 (frame 449), the cloud in the foreground remains visible somewhat longer, gradually dissolving and loosing its convective appearance. The strong wind blowing through Schneefernerscharte and over Schneefernerkopf increasingly prohibits further growth of the cloud. Since the convective clouds in the vicinity disappear it must be concluded that the cloud in the foreground is generated not by buoyancy alone but also by mechanisms associated with the flow over the ridge. Following criterion IV the cloud thus comes closer and closer to a pure banner cloud. The bits of clouds visible at the end of the sequence at 17:57 (frame 648) clearly indicate a lee vortex; they are not convective anymore. According to criterion IV this phenomenon is now a banner cloud.

5.7 Snow blown off the mountain

The Glossary of Meteorology (Glickman, 2000) says that a banner cloud "…strongly resembles snow blowing off the peak (snow banner), and it is often difficult to tell the difference". Figure 10 illustrates this point. Obviously, it is not straightforward to tell whether the movie shows a cloud consisting of droplets or snow blown off the ridge. However, there are indications that this is blowing snow. For instance, note the short light flashes in the foreground presumably originating from snow crystals. Also, the snow banner appears to be more transparent than a banner cloud consisting of water droplets. In addition, the banner becomes better visible by the time the solar illumination comes from the front. The latter suggests that the banner is very thin, because it requires an illumination with shadow in the background for it to be clearly visible. In addition, it suggests that the particles forming the banner reflect the light rather than scatter it in all directions (like cloud droplets would do). The wind speed measured at the Zugspitze summit weather station is as high as 9 m/s, with even stronger gusts. This is the strongest wind of all the cases presented here. Such high wind speeds render it likely that sufficient amounts of snow are blown away from the surface and appear like a cloud in the air. The strongest argument in favor of blowing snow, however, is the relative humidity, which we measured continuously on the cable car between the summit and Zugspitzplatt on the southern side of the mountain. During the entire afternoon the relative humidity between 2500 m and 2962 m was around 40% most of the time and never exceeded 50%. The same low relative humidities were observed at the "Umweltforschungsstation Schneefernerhaus" (UFS) at the southern slope of the mountain (see Fig. 3).

So we believe that the sequence is an example for blowing snow, and according to criterion II we are not dealing with a banner cloud.

6 Summary

This paper presents a comprehensive definition of "banner clouds". It is primarily based on an extensive collection of time lapse movies taken at Mount Zugspitze, but previous theories of this phenomenon are also taken into account. The definition includes the following four criteria: (I) Banner clouds must be directly associated with and attached to the mountain. They must not appear on the windward side of the mountain. (II) The cloud must originate from condensation of water vapour contained in the air (rather than simply be blowing snow). (III) The cloud must be persistent. (IV) The banner cloud must not be of convective character; this means that the cloud updraft is not due to positive buoyancy, but instead directly associated with the flow over and around the mountain. These criteria were illustrated and discussed by specific examples provided in the form of stills and time lapse movies. The most contentious of our criteria is (IV), because there is a continuous transition between dynamically driven banner clouds and convectively driven cumulus clouds. Our examples also prove that banner clouds are not restricted to peaked mountains (as postulated by Geerts, 1992a), but may occur on nearly horizontal ridges as well.

Further progress in understanding banner clouds requires the combination of dedicated observations and fine scale modelling. For instance, it remains to work out the difference between near two-dimensional and fully three-dimensional geometry regarding the formation and likelihood of occurrence of banner clouds. This and other issues will be subject of forthcoming publications.

Appendix A

Viewing the movies

The movies presented here are of type MPG 1. They are embedded into this PDF-document with the LaTeX-package `movie15` which follows the Adobe PDF specification version 1.5. Using the Windows Adobe-Acrobat-Reader version 6.0 or higher, the movies can be viewed by double clicking on the symbol on the top left corner of every still image. The program then starts the MPG standard viewer defined on the system. If this does not work, it is possible to extract the embedded files from the PDF document by right clicking on the symbol or via the Attachment tab of the Acrobat-reader (menu View/Navigation Tabs/Attachments). The movies then can be saved and viewed with any MPG-software on your system.

It currently seems impossible to open or extract the embedded video files with other PDF-readers like GHOSTVIEW or the PDF-viewer embedded in KONQUEROR. If you want to use these PDF-readers, you can download a ZIP-archive from http://www.atmos-chem-phys.net/7/2047/2007/acp-7-2047-2007-supplement.zip which contains the videos. By extracting this ZIP into the same directory as the PDF, the text "movie `mXX.mpg`" below every still image becomes a clickable link to the corresponding movie.

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